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# A Review of Critical Scouring Velocity of Compact Roof Aggregate

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## ABSTRACT:

This paper provides a review of previous studies on how various building parameters affect the critical scouring velocity of roof aggregate, and how these data can be used from a risk mitigation point of view. The review suggests that the data are available only up to a building height of 45 m, with and without parapets, and with no roof-mounted equipment. However, loosely-laid roof aggregate is currently used up to an approximate building height of 150 m in some cities, and these buildings usually have substantial roof-mounted equipment and parapets that are typically less than 1.8 m high. The available data may not necessarily provide reliable recommendations when extrapolated to these high-rise buildings as the aerodynamics of low-rise to high-rise buildings are different and can be influenced by the presence of roof-mounted equipment. The paper concludes by suggesting confidence limits when extrapolating existing data and identifying areas that need further research to address the critical scouring velocity of loosely-laid roof aggregate for low-rise and high-rise buildings.

**KEYWORDS:** Wind-borne debris; loosely-laid roof aggregate; critical scouring velocity; building aerodynamics; wind loads.

## 1. INTRODUCTION

Extensive evaluation by Minor (1994) and Kareem and Bashor (2006) after significant hurricane events demonstrated that wind-borne debris is one of the primary causes of building envelope damage. Wind-borne debris arises from a variety of sources including building components such as tiles, shingles, metal sheeting, timber structural members of low-rise buildings, and loosely-laid roof aggregate such as roof gravel on built-up roofs (BUR) (Owen, 2015, Holmes, 2010, Kaye, 2017). Wills et al. (2002) classified wind-borne debris into three generic types: (a) compact, (b) rod, and (c) sheet. Debris, when picked up by the wind, can accelerate and travel long distances, and gain significant momentum before reaching the ground or downstream buildings. Typical damage includes broken windows and penetration of the building envelope. It is important to note that, once the envelope of the building is breached, internal

pressurization of the building can cause progressive failure of various building components, leading to extensive damage and additional wind-borne debris, which can further impact surrounding buildings. Hence, wind-borne debris poses a significant hazard and, thus, arises the necessity to understand this hazard and the influencing parameters to develop risk mitigation solutions.

Crushed stone or gravel used as roof ballast that can be classified as the compact type is of interest in this review and will be the only type that will be explored further. Karimpour and Kaye (2012) provide a clear and succinct review of the interaction of loose particles with fluid flow in the context of sediment transport and wind erosion based on the work by Shields (1936) and Bagnold (1937), respectively. Shields (1936) proposed that critical shear stress for sediment transport in non-dimensional form can be written as

$$\frac{\tau_c}{(\rho_p - \rho_f)gd} = \frac{\rho_f u_{*c}^2}{(\rho_p - \rho_f)gd} = \frac{u_{*c}^2}{((\rho_p - \rho_f)/\rho_f)gd} = Fr_*^2 \quad (1)$$

where  $\tau_c$  is the critical shear stress,  $\rho_p$  is the density of the particle,  $\rho_f$  is the density of the fluid,  $d$  is the particle diameter,  $u_{*c}$  is the friction velocity, and  $g$  is the acceleration due to gravity. The left-hand side of the equation is also called the critical Shields parameter, which is the square of the densimetric Froude number ( $Fr_*$ ). Karimpour and Kaye (2012) suggest that the underlying physics of sediment transport and wind erosion is similar to that of the wind-borne debris of roof aggregate since, in both cases, the fluid is interacting with loosely-laid particles. They indicated that the Froude number is dependent on

$$Fr_d^2 = f\left(Re_d, \frac{H}{h}, \frac{H}{w}\right) \quad (2)$$

where  $H$  is the parapet height,  $h$  is the building height,  $w$  is the width of the building. The Reynolds number ( $Re_d$ ) and Froude number ( $Fr_d$ ) are calculated using the wind velocity at the top of the parapet ( $U_H$ ) instead of the friction velocity ( $u_{*c}$ ) used in Eq. (1). According to Karimpour and Kaye (2012, 2013), the roof gravel blow-off failure mechanism can be envisioned as a three-part problem:

1. Motion initiation – This is the process through which aggregate is lifted from the roof, out of the cavity formed by the parapets. This part of the problem identifies the building parameters that will affect the roof height velocity, which in turn governs the motion initiation of the roof gravel.
2. Removal – This is the stage that relates the motion initiation and quantifies the aggregate removal rate from the roof. This part of the problem identifies the downwind risk of debris impact.

3. Flight – This stage quantifies the distance the aggregate travels in the downstream direction before impact. This part of the problem identifies the parameters that will affect how far the gravel can travel once it becomes airborne.

*Motion initiation* of wind-borne debris relates to the critical scouring velocity of roof aggregate, which is the primary focus of this review paper. Hence, *removal* and *flight* of wind-borne debris are not discussed here. This paper reviews model-scale wind tunnel experiments that were conducted by Kind (1973, 1974, 1975), Kind and Wardlaw (1976, 1977, 1985), and Kind et al. (1984, 1987) at the National Research Council (NRC) of Canada, Kind (1986) at Carleton University, Phalen Jr. (1984, 1985) at Northeastern University, Karimpour and Kaye (2012, 2013) at Clemson University, and by Kopp (2009) at the University of Western Ontario with the objective to collate all the available experimental data in order to:

- Understand the relationship between Reynolds and Froude number,
- Develop guidelines for risk mitigation for different classes of buildings, i.e., low- and high-rise, and
- Identify areas that need further research.

The following sections describe the details of these experimental studies along with a summary of experimental data, followed by a comparison of critical scouring velocity among all studies. Some conclusions are drawn, and guidelines are presented along with assumptions that identify areas for future research.

## 2. SUMMARY AND ANALYSIS OF PREVIOUS RESEARCH

### 2.1 Data from NRC Canada

This section summarizes the work done at the National Research Council (NRC) of Canada by Kind and his coworkers. The work has been summarized in publications by Kind (1973, 1974, 1975), Kind and Wardlaw (1976, 1977, 1985), and Kind et al. (1984, 1987). These studies address critical scouring velocities of loosely-laid roof aggregate as a function of building height, parapet height, gravel size, along with the effects of building corners covered with paver blocks instead of roof gravel.

#### 2.1.1 Experimental Setup

All the dimensions including gravel sizes and parapet heights were tested at a model scale of 1:10. Three identical building blocks with equivalent full-scale dimensions (Length x Width x Height) of 22.9 x 4.6 x 4.6 m were constructed and used in combinations to model various building heights and plan dimensions for low-rise building (Kind, 1973). Another low-rise building size that was also tested was 13.7 x 13.7 x 2.7 m. Two high-rise building sizes (i.e., buildings that are taller than wide) were tested corresponding to

9.1 x 9.1 x 22.9 m and 18.3 x 9.1 x 22.9 m. Various parapet heights were tested ranging from 0.06 m to 1.37 m. Three different gravel sizes corresponding to 22.9 mm, 38.1 mm, and 72.1 mm (in equivalent full-scale) were tested, with the gravel spread to depths of about 63.5 mm, 76.2 mm, and 127 mm. Additional experiments also consisted of including paving blocks in the corner of the roof, which is defined by the parameters  $a$  and  $b$  as shown in Fig. 1. (The paving blocks were included to understand how the scouring velocity changes with the influence of corner vortices.) However, little information regarding the turbulence characteristics or turbulence spectra of terrain simulation is provided, except for the reported gust factors for different building heights, which are summarized in Table 1.

### 2.1.2 Experimental Data

Table 2 summarizes the equivalent full-scale experimental data from Kind's experiments. Kind (1975) identified four different wind speeds ( $U_{C1}$ ,  $U_{C2}$ ,  $U_{C3}$ , and  $U_{C4}$ ) defined as: (i)  $U_{C1}$  is the wind speed at which one or more stones are first observed to move an appreciable distance. No gravel will leave the roof at this wind speed; (ii)  $U_{C2}$  is the wind speed above which scouring of stones would continue more or less indefinitely as long as the wind speed is maintained. No gravel will leave the roof at this wind speed; (iii)  $U_{C3}$  is the wind speed at which few stones are observed to leave the roof by going over the upstream parapet (AB in Fig. 1); (iv)  $U_{C4}$  is the wind speed at which a few stones are observed to leave the roof by going over the downstream parapet (BC in Fig. 1). The four different wind speeds summarized in Table 2 are 1-s gust wind speeds at roof height. These values are obtained by multiplying the mean hourly wind speeds at the 9.1 m above the ground with their respective gust factors corresponding to building heights summarized in Table 1.

Kind and Wardlaw (1976) noted that the motion of the stones lasts for a limited time when subjected to wind speeds between  $U_{C1}$  and  $U_{C2}$ . The stones start to scour continuously when wind speed is greater than or equal to  $U_{C2}$ . The uncertainty in the wind speed around  $U_{C2}$  is about 10% as it is difficult to identify constant scouring during the experiments. The uncertainty around  $U_{C3}$  and  $U_{C4}$  is around 20 % as a small number of stones could leave the roof at lower wind speeds than those noted in Table 2. Little information is provided as to how these uncertainties were calculated by Kind and Wardlaw (1976). Based on the description of different critical velocities,  $U_{C2}$  is the critical scour velocity that is of importance in this study as this speed relates to the wind speed just before failure of the gravel and will be analyzed further in the following discussion.

### 2.1.3 Building Classification

Kind and Wardlaw (1976) classify a building as low-rise when

$$2.5(h + 3H) \leq l \text{ and } 2.5(h + 3H) \leq w \quad (3)$$

where  $h$  is the height of the building,  $H$  is the height of the parapet,  $l$  is the length of the building, and  $w$  is the width of the building. Even though Kind and Wardlaw (1976) did not provide any justification for Eq.(3), the possible intent would have been to identify the limiting case of the low-rise building that is strongly influenced by the corner vortices. SEAOC-PV2 (2017) uses a similar equation, i.e., wall aspect ratio ( $l/h$  or  $w/h \leq 2.5$ ) to limit the effect of corner vortices, as the corner vortices do not get much stronger for larger wall aspect ratios. However, based on the data presented in Table 2, Eq. (3) does not classify building heights of 9.1 m and 13.7 m as low-rise even though the height is less than the least horizontal dimension. Therefore, a new building classification is proposed for low- to mid-rise building as

$$2.5(h + 3H) > l, 2.5(h + 3H) > w, h < l, \text{ and } h < w \quad (4)$$

which accounts for building heights of 9.1 m and 13.7 m. Buildings which satisfy equation (4) are termed as low- to mid-rise herein. Kind and Wardlaw (1976) classifies a building as high-rise when

$$h \geq (l + w) \quad (5)$$

However, based on the data presented in Table 2, Eq.(5) only classifies buildings with dimensions 9.1 x 9.1 x 22.9 m as high-rise. Buildings with dimensions 9.1 x 18.2 x 22.9 m do not agree with Eq. (5). Therefore, a new high-rise building classification is proposed as

$$h < (l + w), h > l, \text{ and } h > w \quad (6)$$

which leads to the building with dimensions 9.1 x 18.2 x 22.9 m being classified as another class of high-rise. Equation (5) is termed as high-rise I and Eq. (6) is termed as high-rise II, herein.

#### 2.1.4 Assumptions

Kind (1975) assumed that the same 1-s gust wind speeds in Table 2 at the rooftop level would cause failure of roof gravel for geometrically similar buildings of different heights for a particular gravel size. Based on the building classifications presented in Section 2.1.3, this assumption implies that, as long as the ratios  $l/h$  and  $w/h$  fall within a range, the different critical velocities presented in Table 2 can be assumed to be independent of the building height. Akon (2017) suggested that roof height wind speed is constant only when the ratios of  $l/h$  and  $w/h$ , and the longitudinal turbulence intensity at the building height are the same based on a study of the different size of low-rise buildings. Hence, it can be concluded that Kind's (1975) assumption is reasonable, considering that it is a modest relaxation of

criteria suggested by Akon (2017), which allows one to generalize the results from the available experimental data.

### 2.1.5 Critical Scouring Velocity

In order to account for various building parameters and the gravel sizes that influence the critical scouring velocity, Kind and Wardlaw (1976) define the critical scouring velocity as being dependent on the three variables in the following expression

$$U_{c2} = (F_S)(F_P)(U_{C_{ref}}) \quad (7)$$

where

$F_S$  = gravel size factor that accounts for the size of the gravel;

$F_P$  = parapet height/paving block array factor that accounts for the parapet height and paving block dimensions;

$U_{C_{ref}}$  = Reference critical wind speed that is assumed to be constant for each class of building.

These variables will be discussed in the following sections.

### 2.1.6 Gravel Size Factor ( $F_S$ )

Kind and Wardlaw (1976) use Froude scaling to convert model-scale data to full scale with the assumption that the Froude number is constant and independent of the Reynolds number. This assumption implies that the scouring velocity at full scale can be obtained from model-scale experiments using (Karimpour and Kaye, 2012)

$$U_{FS} = U_{MS} \sqrt{\frac{d_{FS}}{d_{MS}}} \quad (8)$$

where the subscript  $FS$  indicates full scale and  $MS$  indicates model scale, while  $d$  is the particle diameter.

Kind and Wardlaw (1976) termed the ratio  $\sqrt{d_{FS}/d_{MS}}$  as the gravel size factor ( $F_S$ ), and suggested that

Eq. (8) can also be used to scale the experimental data for different gravel sizes, when the critical scouring velocity is known for a particular gravel size as

$$U_{required\ gravel\ size} = U_{known\ gravel\ size} \sqrt{\frac{d_{required\ gravel\ size}}{d_{known\ gravel\ size}}} \quad (9)$$

Equation (9) is plotted in Fig. 2, where Kind and Wardlaw (1976) used 19.1 mm as the reference (or known) gravel size and presented  $F_S$  for the critical scouring velocity that can be calculated for other gravel sizes.

### 2.1.7 Parapet Height/Paving Block Array Factor ( $F_P$ )

Kind and Wardlaw (1976) present parapet height/paving block array factors ( $F_P$ ) (see Fig. 3) that account for the parapet height and paving block dimensions for (a) low-rise, (b) high-rise I, and (c) high-rise II buildings. As the interdependence of the building shape, parapet height, and paving block array cannot be individually quantified, Kind and Wardlaw (1976) defines the factor  $F_P$  as the ratio

$$F_P = \frac{U_{C(d)}}{U_{C_{ref}}} \quad (10)$$

where  $U_{C(d)}$  is the roof height critical velocity for a particular gravel size ( $d$ ) and  $U_{C_{ref}}$  is an arbitrarily chosen reference critical wind speed (see Section 2.1.8).

Kind and Wardlaw (1976) present the parapet height/paving block array factors ( $F_P$ ) as a function of the parapet height ( $H$ ) divided by the building height ( $h$ ) for a low-rise building ( $h \ll l, w$ ), and by the building width ( $w$ ) for a high-rise building ( $h \gg l, w$ ), to take advantage of the universality of the data regardless of the actual height, length and width of the building. Not many details are provided in the report by Kind and Wardlaw (1976) on how  $F_P$  was obtained except for Eq. (10). They present factors  $F_{P1,2}$  (see Fig. 3) used to calculate  $U_{c1}$  and  $U_{c2}$ , and  $F_{P3}$  (not shown), to calculate  $U_{c3}$ . Kind and Wardlaw (1976) noted that, in the case of  $U_{c4}$ , since the stones must travel the whole roof length to leave the rooftop from the downstream parapet, the speed of the stone cannot be assumed to be negligible compared to the speed of the airflow. Hence, the analysis used for velocities  $U_{c1}$ ,  $U_{c2}$ , and  $U_{c3}$  cannot be used for  $U_{c4}$  to make generalized recommendations. Therefore, Kind and Wardlaw (1976) did not provide any recommendations for  $U_{c4}$ .

### 2.1.8 Reference Critical Wind Speed ( $U_{C_{ref}}$ )

Kind and Wardlaw (1976) recommend using a reference critical wind speed ( $U_{C_{ref}}$ ) of 35.3 m/s, 34.4 m/s, and 29.9 m/s to estimate the critical scouring velocity ( $U_{c2}$ ) when the gravel size is 19.1 mm (i.e.,  $F_S = 1$ ) for low-rise and the two types of high-rise buildings, respectively. Kind and Wardlaw (1976) arbitrarily chose these scouring wind speeds for a particular case with the intent to obtain scouring wind speeds by multiplying the reference critical wind speed ( $U_{C_{ref}}$ ) with appropriate factors to account for the different gravel sizes ( $F_S$ ), parapet height and paving block geometry ( $F_P$ ). However, it can be noted from Table 2,



that Kind (1975) did not perform experiments for a gravel size of 19.1 mm, and Kind and Wardlaw (1976) did not provide any explanation for how  $U_{C_{ref}}$  was estimated for this gravel size.

### 2.1.9 Further Analysis of NRC Data

In the following section, the experimental data summarized in Table 2 will be analyzed to understand the basis for the parapet height/paving block array factor ( $F_p$ ) and the reference critical wind speed ( $U_{C_{ref}}$ ) proposed by Kind and Wardlaw (1976) for a 19.1 mm gravel size.

#### 2.1.9.1 Low-rise Building

From Fig. 3 (a) it can be noted that Kind and Wardlaw (1976) normalized their experimental data by dividing the velocity at  $H/h = 0.1$  for  $a = 0$  and  $b = 0$ , where  $a$  and  $b$  are defined in Fig. 1. For a low-rise building, data (see Table 2) are available for three gravel sizes corresponding to 22.9 mm, 38.1 mm, and 72.1 mm. The corresponding critical scouring velocities of 38.0 m/s, 44.3 m/s, and 55.0 m/s at  $H/h = 0.1$  for  $a = 0$ , and  $b = 0$  are used as reference critical wind speeds ( $U_{C_{ref}}$ ) in Eq. (10) to obtain the parapet height/paving block array factor ( $F_p$ ). It can be noted from Table 2 that, for the same  $H/h$  ratios, multiple values are available from different experiments, in which case the minimum velocity from all available experiments is taken as the reference critical wind speed. The parapet height/paving block array factors ( $F_p$ ) are plotted in Fig. 4 for different gravel sizes and different paver block dimensions. It can be noted from the comparison that the Kind and Wardlaw (1976) proposed  $F_{p1,2}$  curves compare well with the experimental data. However, there are few data points ( $a = 0.25 h$ ,  $b = 0.25 h$ ,  $a = 0.5 h$ ,  $b = 1.0 h$ , and  $a = 1.0 h$ ,  $b = 2.0 h$ ) that suggest that the corresponding  $F_{p1,2}$  curves were based partially on judgment since no functional form based on mechanics is provided.

The next question that needs to be addressed is the basis for the reference critical wind speed ( $U_{C_{ref}}$ ) of 35.3 m/s proposed by Kind and Wardlaw (1976) for a gravel size of 19.1 mm. Figure 5 plots the critical scouring wind speed for different gravel sizes. The reference critical wind speed ( $U_{C_{ref}}$ ) corresponding to a gravel size of 19.1 mm is assumed to be obtained by linearly extrapolating the data, which yields a value of 36.4 m/s. Comparing reference critical wind speeds of 35.3 m/s and 36.4 m/s, it can be noted that the difference of the Kind and Wardlaw (1976) recommended reference critical wind speed is approximately 3%, which is within the estimated uncertainty of 10% for the experimental data. Hence, it can be stated that the reference critical wind speed proposed by Kind and Wardlaw (1976) to be used with the Parapet Height/Paving Block Array Factors ( $F_p$ ) agree reasonably well with the experimental data presented in Table 2.

Since the critical scouring wind speeds for different gravel sizes are available from experimental data, Eq.(9) can be verified. The critical scouring velocities for different gravel sizes (i.e., 22.9 mm, 38.1 mm,

and 72.1 mm) can be calculated using Eq.(9) with a reference critical wind speed ( $U_{C_{ref}} = 35.3$  m/s) proposed by Kind and Wardlaw (1976) for a gravel size of 19.1 mm. This is shown as the dashed line in Fig. 6 compared with experimental data shown by the solid line. It can be noted that the critical scouring velocities suggested by Kind and Wardlaw (1976) for different gravel sizes are higher compared to what is obtained from the experimental data. These higher critical scouring velocities imply that the gravel can sustain higher wind speeds before they start to scour, when compared to what the experimental data suggest. The difference in the velocities noted in Fig. 6 is much higher for larger gravel sizes. Therefore, it can be concluded that the gravel size factor (Eq.(9)) proposed by Kind and Wardlaw (1976) based on the assumption that Froude number is constant and independent of Reynolds number is not completely accurate and needs to be investigated further.

### **2.1.9.2 High-Rise Building I and High-Rise Building II**

From Fig. 3 (b and c) it can be noted that Kind and Wardlaw (1976) normalized their experimental data by dividing the critical velocity at  $H/w = 0.025$  for  $a = 0$  and  $b = 0$  instead of  $H/h = 0.1$ ,  $a = 0$ , and  $b = 0$  for a low-rise building. An analysis similar to that for the low-rise buildings (see Section 2.1.9.1) is performed for the high-rise buildings from Table 2, and hence the details of the analysis are not presented here. The comparison (Fig. 7 and Fig. 9) indicates that the data agree with the Parapet Height/Paving Block Array Factor ( $F_P$ ), but there are limited data when compared to those for the low-rise buildings. These scouring velocity comparisons (Fig. 8 and Fig. 10) indicate that Kind and Wardlaw (1976) recommend higher critical velocities for roof gravel failure than the experimental data, especially for gravel sizes greater than 38.1 mm.

### **2.1.9.3 Revised Gravel Size Factor**

In order to correct the critical velocities obtained based on Kind and Wardlaw (1976) recommendations, a velocity correction factor is proposed that is obtained by dividing the actual scouring velocities from the experiments with the scouring velocities obtained from Kind and Wardlaw (1976) recommendations. These are plotted in Fig. 11 for low-rise buildings. Similar correction factors can be obtained for high-rise building I and high-rise building II. These velocity correction factors can be combined with the gravel size factor ( $F_S$ ) discussed in Section 2.1.5, and a revised gravel size factor can be obtained as shown in Fig. 12.

Based on the curves presented in Fig. 12, it can be noted that the revised gravel size factor for the low-rise building deviates the most from what is recommended by Kind and Wardlaw (1976) especially for gravel sizes greater than 25 mm. On the other hand, the revised gravel size factor for high-rise I appears to be the closest match with what is recommended by Kind and Wardlaw (1976), even though it deviates

substantially for gravel sizes greater than 35 mm. The revised gravel size factor for high-rise II varies between that of low-rise and high-rise I, depending on the gravel size.

## **2.2 Data from Carleton University**

The section summarizes the measurements from Kind (1986) at Carleton University at a model scale of 1:60 and 1:120 for five model-scale gravel sizes ranging from 0.2 mm to 0.72 mm equivalent to a full-scale gravel size ranging from 21 mm to 43.2 mm. Table 3 summarizes the critical scouring velocity ( $U_{c2}$ ) results from these experiments.

### **2.2.1 Experimental Setup**

Kind (1986) retested the 1:10 (Kind, 1975) model-scale experiments at smaller scales of 1:60 and 1:120 to investigate the effect of Reynolds number. The experiments were carried out in the Carleton University wind tunnel having dimensions of 1.2 m high x 1.7 m wide x 12 m long. Natural silica was used to model the gravel size corresponding to five model-scale sizes of 0.2 mm, 0.35 mm, 0.51 mm, 0.63 mm, and 0.72 mm.

### **2.2.2 Experimental Data**

The critical velocities  $U_{c1}$ ,  $U_{c2}$ , and  $U_{c3}$  were measured similar to those in Kind's 1:10 scale experiments (Kind, 1975); however, only data for  $U_{c2}$  were presented in the publication (Kind, 1986). Figure 13(a) shows the comparison of model-scale critical scouring wind speeds at 1:60 and 1:120 scales (Kind, 1986) compared with 1:10 model-scale experiments (Kind and Wardlaw, 1976) for a low-rise building. It should be noted that the data presented in Fig. 13(a) are model-scale data, whereas the 1:10 model-scale data from Kind and Wardlaw (1976) were used for a gravel size of 19.1 mm. Based on these comparisons, Kind (1986) noted that the model-scale data are subjected to Reynolds number effects and proposed a correction factor. However, Kind (1986) did not present how the corrected data would compare with their 1:10 model-scale experiments. Karimpour and Kaye (2012) presented the corrected data (presented in Fig. 13 (b)) and concluded that the corrected data are approximately 30 % lower than the 1:10 model-scale data from Kind and Wardlaw (1976). They suggest that the correction method proposed by (Kind, 1986) does not completely eliminate the Reynolds number effects and conclude by stating that the Reynolds number effects can only be fully addressed by conducting full-scale experiments.

### **2.2.3 Further Analysis of Carleton University Data**

The data presented in Fig. 13 are comparing the Kind and Wardlaw (1976) 1:10 model-scale data for a full-scale gravel size of 19.1 mm with Kind's (1986) 1:60 and 1:120 model-scale data for different gravel sizes. This comparison of data at different model scales is not appropriate because it violates the Froude scaling relationship. Hence, Fig. 14 presents the comparison of Kind and Wardlaw (1976) and Kind's

(1986) model-scale data converted to full-scale using the Froude Scaling relationship presented in Eq. (8). Kind and Wardlaw (1976) data for different gravel sizes were estimated using the revised gravel size factors presented in Fig. 12.

Based on the comparisons of critical scouring velocity ( $U_{C2}$ ) at different gravel sizes in Fig. 14, it can be noted that the 1:60 model scale compares reasonably well with 1:10 model-scale data, whereas the 1:120 model scale predicts scouring velocities that are much higher than those from the 1:10 model-scale data. Another interesting observation is that the large gravel size at 1:120 model scale has a relatively smaller difference in  $U_{C2}$  compared to 1:10 model-scale data for smaller gravel sizes, suggesting that the physical gravel sizes used in the model-scale experiments have an influence on  $U_{C2}$ . These comparisons contradict the argument by Kind (1986) that aerodynamic drag on ballast stones is higher in small-scale tests compared to full-scale, predicting lower full-scale critical scouring wind speeds when calculated based on data obtained from model-scale experiments. However, the possible reasons for this trend are not clear. It can be stated that uncertainty in experiments is higher when smaller model scales are used to obtain critical scouring velocities. However, the correction factor proposed by Kind (1986) to account for Reynolds number effects may not be appropriate and needs further research.

### **2.3 Data from Northeastern University**

This section provides a summary of the work done by Phalen (1984, 1985) and Phalen and Smith (1984) on the mechanics of gravel instability, scour, and movement under wind conditions for single-ply loosely-laid roof membranes. Phalen (1984) conducted full-scale experiments to explain the scour mechanism of stone ballast on a single-ply loosely-laid membrane. Figure 15 shows the experimental setup, which consists of a cube-shaped building. The full-scale platform measured 3 x 3.6 m. However, information about the building height is not reported. Parapets ranging from 0 to 0.9 m in increments of 0.15 m were tested. The free-stream wind was developed from a 250 HP Continental 7-cylinder radial engine that was connected to a 1.8 m propeller drive. Wind speeds in the range of 20.1 to 55.9 m/s were achieved during the experiments. The geometry of the fans and the test structure was developed by trial and error to attain an airstream 3.7 m wide and about 1.2 m thick when impinging on the structure. An observation platform was used for photography during the experiments.

The test platform consisted of a single-ply Ethylene Propylene Diene Monomer (EPDM) membrane loosely-laid on a structural deck. The membrane was sealed entirely along the edges by a flashing system such that the roof system was airtight. The test measurements were provided by 22 Pitot tubes. In addition, four monitors were used to measure wind speed on the roof. The direction of the wind that impinged on the platform corresponded to  $45^\circ$ , which represented the severest condition based on the work done by Kind and Wardlaw (1976). For each wind speed, the surface pressure was recorded at the

manometer locations. Phalen (1984) noted that each probe yielded a constant coefficient of pressure and suggested using Bernoulli's equation in formulating a mathematical procedure to estimate scouring velocity based on surface pressure variation on the roof as a function of parapet height.

### **2.3.1 Test Observations**

Phalen (1984) observed that, when the wind interacted with the roof membrane, the pressure differential had the effect to make the membrane expand upwards and caused the membrane to flutter, vibrate, and oscillate, which cannot be simulated in model-scale experiments as rigid model-scale buildings are used.

### **2.3.2 Gravel Scour Wind Speed**

Phalen (1984) measured the wind speed at which scour occurs. Table 5 summarizes the critical scouring velocity ( $U_{c2}$ ) from these experiments and Figure 16 shows the comparison of wind speed as a function of stone diameter between Phalen (1984) and Kind and Wardlaw (1976) for a low-rise building. In spite of the differences in the experimental approaches, the comparison indicates that Phalen's (1984) wind speeds match those from Kind and Wardlaw (1976).

### **2.3.3 Differential Pressure**

Phalen (1984) measured the differential pressure at the rooftop level during the experiments. He developed a theoretical model to connect the differential pressure on the roof with the gravel resistance for the case when the stone becomes wind-borne. The underlying assumption for this theoretical model is that roof pressure coefficients are constant, and that the Bernoulli's equation can be used to adjust the velocity based on the constant surface pressure coefficients. It should be noted that the surface pressure coefficient on the roof is not constant and changes with time because of the separation reattachment and corner vortices, while cause Bernoulli's equation not to hold near a roof surface (Wu et al., 2017). Phalen (1984) reported a constant pressure coefficient as the measurements were performed using manometers which will only measure mean values when tested for a particular wind direction, which is  $45^\circ$ , in this case. Hence, the analysis is not presented here as the mathematical model provided by Phalen (1984) is not appropriate and is not explored further.

## **2.4 Data from Clemson University**

This section summarizes the work conducted at Clemson University by Karimpour (2011) on a 1:20 model-scale building corresponding to full-scale building heights of 3.0, 4.0 and 6.0 m for different parapet heights (0, 0.05, 0.1, 0.3, and 0.5 m), gravel sizes (2.2, 4.6, 7.2, 9.0, 10.2, 14.6, 17.8, 30.9, and 69 mm), and two different particle types (sand and millet). The width of the building spans the whole cross section of the wind tunnel (3 m wide by 2 m high and 28 m long) with small clearances at the end to represent a two-dimensional building. The experiments were conducted to capture the effect of

separating-reattaching flows. Karimpour and Kaye (2012) concluded that the Froude number can be described using the relation for zero parapet heights as

$$Fr_d^2 = 8.1(d_*)^{-0.44} \quad (11)$$

where the non-dimensional particle diameter ( $d_*$ ) is defined as

$$d_* = \left( \frac{Re_d}{Fr_d} \right)^{\frac{2}{3}} \quad (12)$$

The data had more spread when plotted for different parapet heights. However, Karimpour and Kaye (2012) noted that zero parapet height data are not always the worst-case scenario, pointing out that their results follow the observations made for roof pavers blow-off studies (Meroney and Bienkiewicz, 1986). Based on these experiments, Karimpour and Kaye (2012) suggested that Reynolds number is a function of Froude number for particle sizes up to  $d_* = 75$  with no parapet. The data from this study were not used in comparison with other studies as other experiments were mainly focused on an oblique wind angle of  $45^\circ$ , which captures the effect of corner vortices, instead of the perpendicular wind direction of  $0^\circ$  that was used in this study, which captures the effects of separating-reattaching flow.

## 2.5 Data from the University of Western Ontario

The section summarizes the work conducted at the University of Western Ontario by Kopp (2009) on a 1:20 model-scale building with full-scale dimensions of 12.1 x 12.1 x 7.3 m for average gravel sizes of 30 mm and 43 mm. The experiments were conducted with and without surrounding buildings. The experiments measured critical scour velocity as a function of wind direction ( $0^\circ$ ,  $30^\circ$  and  $45^\circ$ ) and parapet height (0.1 m, 0.3 m, 0.9 m, 1.8 m, and 2.7 m at full scale), and also measured the maximum height attained by wind-borne gravels. Table 5 summarizes the critical scouring velocity ( $U_{c2}$ ) from these experiments. The building is classified as a low- to mid-rise based on the definitions presented in Section 2.1.3.

As the  $45^\circ$  building orientation governs the critical scouring velocity (Kind and Wardlaw, 1976), Fig. 17 compares the data from Kind (1975) and Kopp (2009) that are not in accordance with Eq.(4). The data from Table 2 are used to obtain the mean wind speeds at roof height. As the data from Kind (1975) are for a gravel size of 38 mm and these experiments are for a gravel size of 30 mm, Kind (1975) data were adjusted using the revised gravel size factors summarized in Section 2.1.9.3 assuming that the buildings can still be classified as low-rise buildings. The data fit provided in Fig. 17 for a gravel size of 30 mm is expressed as

$$U_{C2} = 112.4\left(\frac{H}{h}\right) + 28.3 \text{ (m/s)} \quad (13)$$

Equation (13) can be converted to a gravel size of 19.1 mm, which is the reference gravel size used by Kind and Wardlaw (1976), with the revised gravel size factors summarized in Section 2.1.9.3. Equation (14) is obtained by multiplying Eq. (13) by a factor of 0.83 using equations summarized in Table 7 for the low-rise building.

$$U_{C2} = 93.3\left(\frac{H}{h}\right) + 23.5 \text{ (m/s)} \quad (14)$$

The mean hourly wind speed obtained by Eq. (14) is converted to 3-seconds gust wind speed by multiplying by a factor of 1.53 using the Durst (1924) curve, shown in Eq. (15)

$$U_{C2} = 142.7\left(\frac{H}{h}\right) + 35.9 \text{ (m/s)} \quad (15)$$

## 2.6 Discussion

The above sections have presented the experimental data from various studies that provide an estimate for the critical scouring velocity. Even though the data from different studies were obtained at different model scales, they were converted to full scale using the Froude scaling relationship along with the revised gravel size factors presented in Section 2.1.9.3. Comparison of the data from different studies provides some useful insights:

- Even though the building height was not a relevant parameter because of the way the experiments were conducted, the full-scale Phalen (1984) data compare reasonably well with 1:10 model scale Kind (1975) data when converted to full-scale.
- Kind (1975) 1:10 model-scale data compare reasonably well with Kind (1986) 1:60 model-scale data when converted to full scale for four different gravel sizes without using the correction factor proposed by Kind (1986). However, there is a clear difference between Kind (1975) 1:10 data and Kind (1986) 1:120 data.
- Kind (1975) 1:10 model-scale data compare reasonably well with Kopp (2009) 1:20 model-scale data when converted to full scale for two different gravel sizes.

These observations suggest that Reynolds number independence can be achieved for specific model scales, whereas Reynolds number effects can be significant and need to be adjusted beyond specific

model scales. With these findings, the next section explores the relationship between Froude and Reynolds number.

### 3. EFFECT OF REYNOLDS NUMBER

In the following discussion, the experimental data from Kind's (1975, 1986) 1:10 and 1:60 model-scale experiments are plotted as  $Fr^2$  vs  $d_*$  (see Fig. 18) as suggested by Karimpour and Kaye (2012). The plot indicates that the curves are similar for different parapet to building height ratios ( $H/h$ ), except that they are shifted along the y-axis as the  $H/h$  ratio increases. This observation provides confidence that the data can be generalized for a certain class/size of buildings. However, there are no sufficient data to plot similar graphs for high-rise buildings, as well as to ascertain whether very small parapets degrade the performance as observed for roof pavers by Meroney and Bienkiewicz (1986).

From Fig. 18, it can be noted that the Froude number is approximately constant with reference to  $d_*$  when the non-dimensional diameter ( $d_*$ ) is greater than 45. This conclusion contradicts the observation made by Karimpour and Kaye (2012), who suggested that, for particle sizes up to  $d_* = 75$  for zero parapet height, the Reynolds number is a function of Froude number. The difference between the two studies is that Karimpour and Kaye (2012) experiments (shown by the dashed line in Fig. 18) were conducted for  $0^\circ$  wind direction compared to  $45^\circ$  in Kind's (1975) studies. Although  $d_*$  should only be dependent on the wind shear and not on the wind angle or the building geometry, further research is required in order to explain fully these observed differences.

To estimate the physical particle diameter range, the particle diameter can be calculated by rewriting Eq. (1) as (Karimpour and Kaye, 2012)

$$d = \frac{d_*}{\left[ \left[ \frac{\rho_p - \rho_a}{\rho_a} \right] \frac{g}{v_a^2} \right]^{\frac{1}{3}}} \quad (16)$$

where

$\rho_a$  = density of air can vary from 1.6 kg/m<sup>3</sup> to 1.09 kg/m<sup>3</sup> for temperatures between -48.15 °C to 51.85 °C.

$\rho_p$  = density of the particle which is pea gravel or crushed stone can vary between 1500 kg/m<sup>3</sup> when dry to 2000 kg/m<sup>3</sup> when wet.

$v_a$  = Kinematic viscosity of air can vary between  $0.935 \times 10^{-5}$  (m<sup>2</sup>/s) at -48.15 °C to  $1.807 \times 10^{-5}$  (m<sup>2</sup>/s) at 51.85 °C.

$g$  = acceleration due to gravity is 9.81 m/s<sup>2</sup>.



The calculated particle diameters are summarized in Table 6 for a different range of particle densities. It is noted that, when the particle diameter ( $d$ ) is greater than approximately 1.3 mm, the Froude number is constant with reference to particle diameter ( $d$ ) or is independent of Reynolds number. This conclusion suggests that the experimental data from Kind and Wardlaw (1976) can be treated as if the Froude number and the Reynolds number are independent of each other, as the smallest model-scale gravel size that was tested is 2.3 mm which in full scale is 23 mm. This conclusion also implies that extrapolating the data from model scale to full scale using the Froude number is valid for Kind and Wardlaw (1976) data and University of Western Ontario data when corner vortices are the dominant vortical structures that interact with roof aggregate.

#### 4. EXTRAPOLATION LIMITS

In general, the experimental data can be extrapolated beyond the range of tested parameters. However, identification of the limits beyond which the extrapolated results may not be representative of the original data set is a challenging task. Therefore, an approach in the following discussion will be used to define these limits so that the recommendations based on the extrapolated data can be used with some confidence. As there is limited data, the extrapolation limits are presented for only two building classifications, i.e., low-rise and high-rise, contrary to four building classification presented in Section 2.1.3. The limits for low-rise are presented by combining the data from low-rise and low- to mid-rise buildings and for high-rise are presented by combining the data from high-rise I and high-rise II.

In order to define the extrapolation limits, the data from the low- to the mid-rise building are used as the data come from two sources, i.e., from Kind's (1975) and Kopp (2009). There are no other additional data for other building dimensions except Kind (1975). Figure 19 compares the Kind (1975) and Kopp (2009) data by developing the relationships individually. It can be noted that, even though Kind's data are available only up to a parapet height of 1.4 m, when extrapolated they can predict the scouring velocities up to a parapet height of 2.7 m with reasonable accuracy. Hence, it can be stated here that data can be extrapolated up to a parapet height twice what was tested in the experiments for similarly sized buildings. However, this finding, which is based on limited available data, needs to be further justified when additional experimental data become available. Therefore, it is recommended that the extrapolation be conservatively capped at 50 % higher than the maximum parapet height tested by Kind (1975) in his experiments for low- and mid-rise buildings where there is no additional data to support the extrapolation. Accordingly, a parapet height of 2.0 m is recommended as the extrapolation limit for low- and mid-rise buildings.

For high-rise buildings, only Kind's (1975) data are available from tests up to 0.9 m. As no additional data are available for high-rise buildings similar to low- to mid-rise buildings, it will be assumed here that the 50% higher parapet height value conservatively proposed for low- to mid-rise buildings will also apply, i.e., 1.4 m will be taken as the limit for high-rise buildings. Any recommendations for parapet heights greater than 1.4 m should be treated as having low confidence.

Based on the above discussion, Fig. 20 presents a visual representation of the confidence limits for the recommended parapet heights for different building classifications. The top-row plots show the building height ( $h$ ) or width ( $w$ ) vs. parapet height ratio ( $H/h$  or  $H/w$ ) for low-/mid-rise or high-rise. The shaded regions indicate the high, medium, and low-confidence regions colored in green, yellow, and white, respectively. The bottom-row plots show the parapet height ratios with building height ( $H/h$ ) vs. building width ( $H/w$ ). The shaded regions indicate the envelope of these ratios to qualify them as low-/mid- and high-rise.

## 5. LIMITATIONS OF EXISTING DATA

There are four main limitations to the data that are reviewed in this paper:

- The primary assumption in the whole analysis is that gust wind speeds at the rooftop level that cause failure of roof gravel remain the same for geometrically similar buildings with different heights for any particular gravel size. Even though this assumption appears to be reasonable based on work by Akon (2017), additional experiments are needed to test the effect of the longitudinal turbulence intensity on scouring velocity.
- The second limitation of the current data as noted by Kind (1986) and Karimpour and Kaye (2012) is that model-scale experiments carried out in wind tunnels are subject to scaling effects as the requirement of constant Reynolds number cannot be satisfied. Even though it was demonstrated from the Kind's (1975, 1986) data that Reynolds number independence could be achieved after a specific particle diameter for low-rise buildings, this assumption needs to be further investigated for other building sizes. Hence, there is a need to quantify the effect of Reynolds number on the scouring velocity of roof gravel by conducting experiments at different model scales, so that model-scale experiments can be adequately extrapolated to full scale for different building dimensions.
- The third limitation of the existing data is that there are no surrounding buildings in the experiments performed by Kind (1975) and the limited number of cases considered at the University of Western Ontario. Therefore, current data could not be directly used to make generalized recommendations. The general trend is that the presence of surrounding buildings can lower the scouring wind speeds based on the findings from the University of Western Ontario experiments. However, it should be

noted that this observation is based on experiments on a low-rise building. Generally, surrounding buildings tend to lower the wind speeds on the target building, but the turbulence intensity could be higher compared to that in an open environment. The existing data do not provide a basis to understand the impact of turbulence intensity on critical scouring velocities. Also, the current available experimental data do not tell us the impact of surrounding buildings on target high-rise buildings. Hence, there is a need to explore the effect of surrounding buildings on critical scouring velocity for different building heights.

- The fourth limitation of the existing experimental data is the lack of information to quantify the effects of roof-mounted equipment on the critical scouring velocity of roof gravel. Indeed, there are no data to address this issue. It may be intuitive to assume that roof-mounted equipment will somehow increase the critical scouring velocity and obstruct the gravel from leaving the roof. However, this scenario is less likely as the roof-mounted equipment can produce its own wind field that can interact with the aerodynamics generated by the building (such as separation reattachment flow and corner vortices) and complicate the mechanism that triggers the motion initiation. Additionally, roof-mounted equipment can cause channeling in some cases and sheltering in others. Until some experimental or numerical studies are performed, it is not straightforward to make recommendations as to how roof-mounted equipment will affect the critical scouring velocity of roof gravel.

## 6. CONCLUSIONS

The review paper provides a summary of the different studies for scouring wind speeds of compact roof aggregate. Kind's (1975) data were reanalyzed with the conclusion that the universal gravel size factor proposed by Kind and Wardlaw (1976) based on Froude and Reynolds number independence is not entirely accurate. Accordingly, revised gravel size factors for different classes of buildings are proposed in this paper. These factors when used with Kind's (1986) 1:60 model-scale data along with Froude scaling compare reasonably well with Kind's (1975) 1:10 model-scale data. On the other hand, the comparison with Kind's (1986) 1:120 model-scale data shows that these are substantially different, suggesting that the proposed revised gravel size factors can only partially negate the effect of the Froude and Reynolds number independence assumed by Kind and Wardlaw (1976). A similar conclusion was also reached through the analysis of data from Kind (1985, 1986), namely that the Froude and Reynolds numbers independence can be achieved when the non-dimensional particle diameter  $d^* \geq 45$  for low-rise buildings. Even though there is not sufficient information to make a similar conclusion for high-rise buildings, the same is assumed to be valid for the recommendations presented in this paper for all building sizes. Additionally, scouring velocity guidelines are proposed for a new class of buildings, i.e.,

low- to mid-rise buildings, by combining the data from Kind (1975) 1:10 model-scale data with Kopp (2009) 1:20 model-scale data. The data analysis demonstrated that the available data can be extrapolated with reasonable confidence up to a parapet height of 2.0 m for low-rise and 1.6 m for high-rise buildings. Extrapolating the available experimental data beyond these parapet heights can be unreliable. The proposed recommendation, even though they are based on available data only up to a building height of 45 m, can be used for all building shapes and sizes for any building height as long as they adhere to the non-dimensional building aspect ratios (i.e.,  $l/h$  or  $w/h$ ) and parapet height ratios (i.e.,  $H/h$  or  $H/w$ ) presented in this study. As a closing, it should be noted that more research is needed to validate the recommendations proposed in this paper to address the limitations of the existing data.

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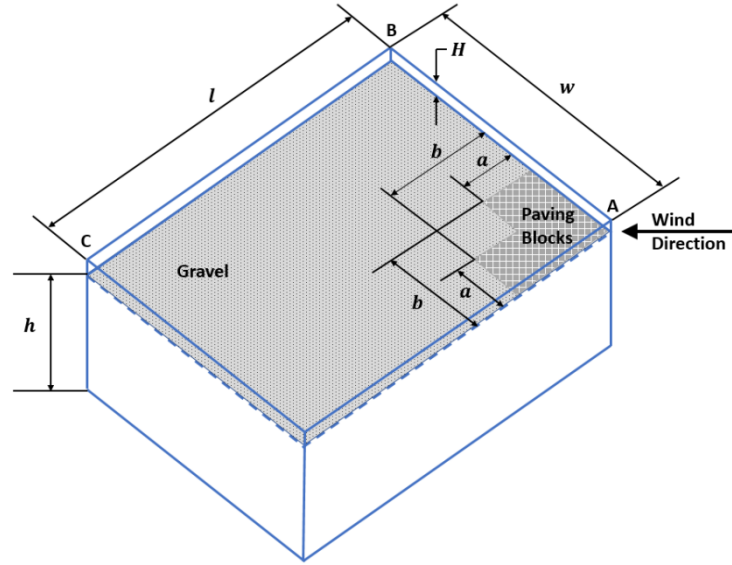
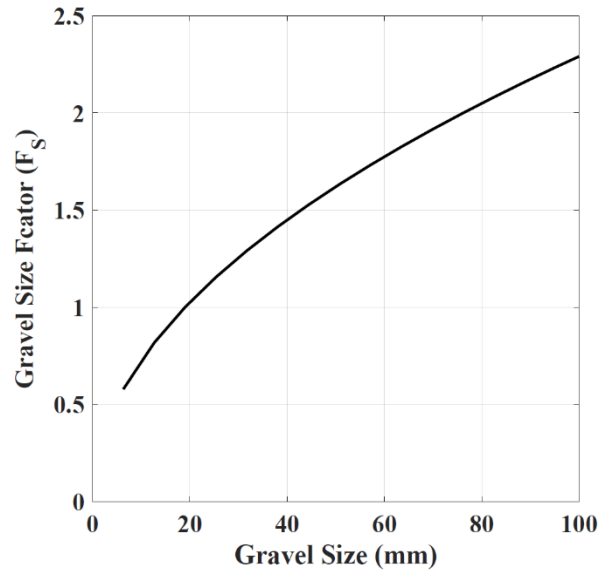


Fig. 1. Definition of different building parameters in Kind's experiments (Kind, 1975).  $H$  is the height of the parapet,  $h$  is the height of the building,  $l$  is the length of the building,  $w$  is the width of the building,  $a$  is the paver block perpendicular to the edge of the roof,  $b$  is the paver block dimension along the edge of the roof,  $AB$  is the upstream parapet, and  $BC$  is the downstream parapet.



608

609 Fig. 2. Gravel size factor.

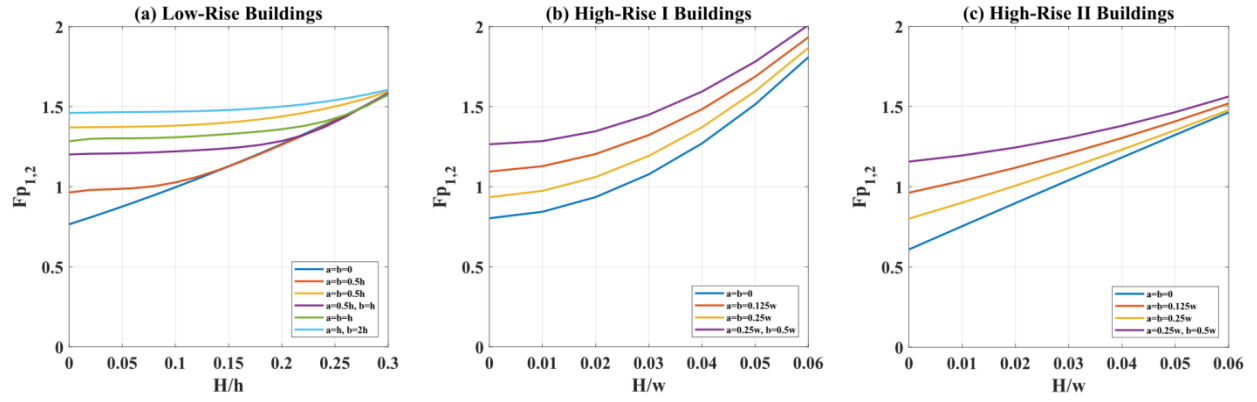


Fig. 3. Factor ( $F_p$ ) that accounts for the combined effect of parapet height and paving block arrays on the critical wind speed for  $U_{c2}$  applied to (a) low-rise, (b) high-rise I, (c) high-rise II buildings (Kind and Wardlaw, 1976)



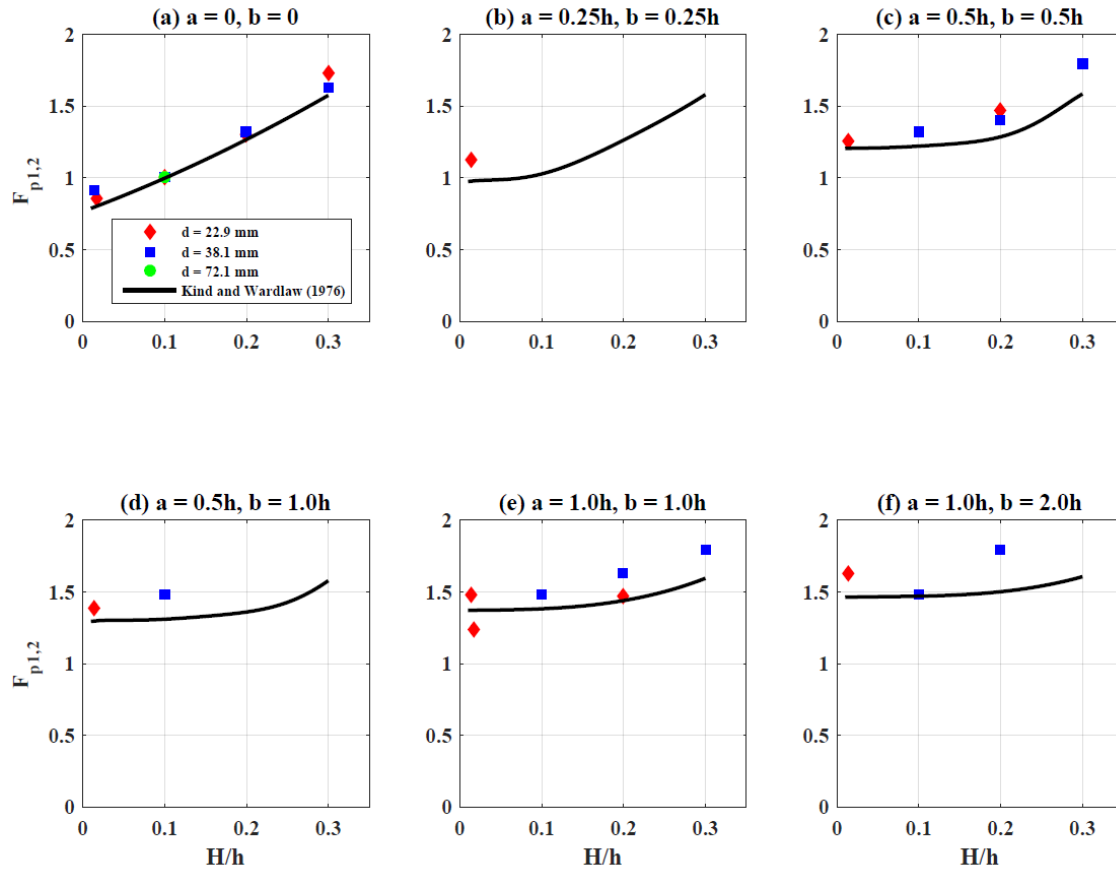
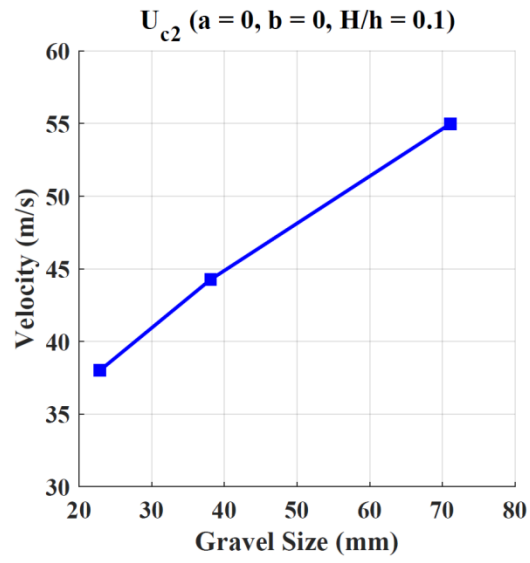


Fig. 4. Comparison of Factor ( $F_{p1,2}$ ) for low-rise building with experimental data from Kind (1975) (see Table 2) for low-rise building divided by critical scouring wind speeds ( $U_{C2}$ ) at  $H/h = 0.1$  for  $a = 0$  and  $b = 0$  for gravel sizes corresponding to 22.9 mm, 38.1 mm, and 72.1 mm.  $a$  and  $b$  are the dimensions of the paver blocks,  $H$  is the height of the parapet and  $h$  is the height of the building.



621

622 Fig. 5. Critical velocity for  $U_{c2}$  of a low-rise building at  $H/h = 0.1$ ,  $a = 0$ , and  $b = 0$ .

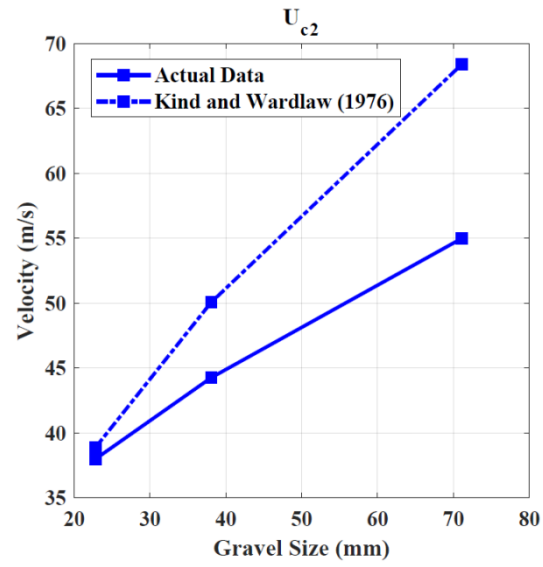


Fig. 6. Comparison of reference velocities from Table 2 with those recommended by Kind and Wardlaw (1976) for a low-rise building.

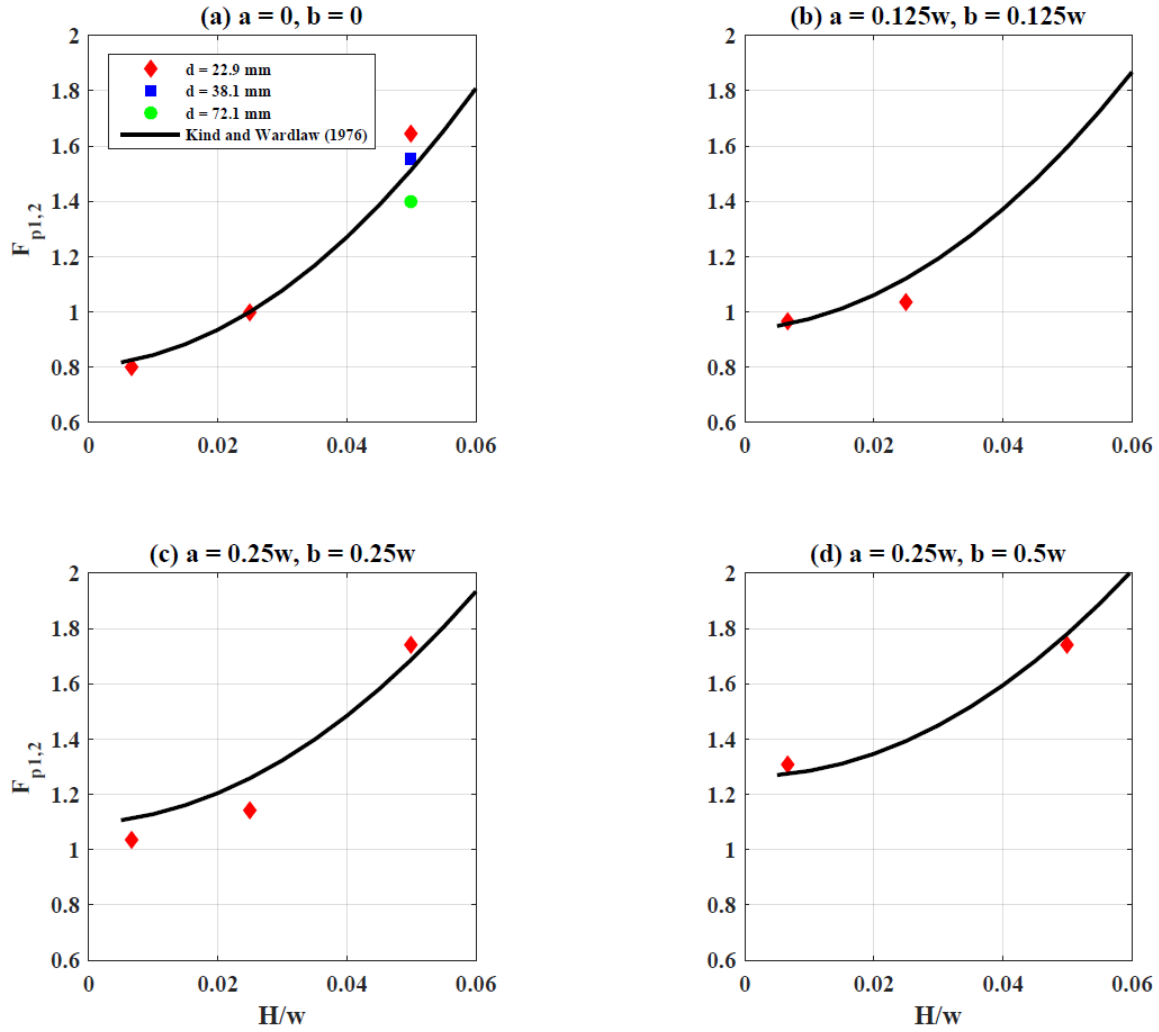


Fig. 7. Comparison of factor ( $F_{p1,2}$ ) for high-rise building I with experimental data from Kind (1975) (see Table 2) divided by critical scouring wind speeds ( $U_{C2}$ ) at  $H/w = 0.025$ ,  $a = 0$  and  $b = 0$  for gravel sizes corresponding to 22.9 mm, 38.1 mm, and 72.1 mm.  $a$  and  $b$  are the dimensions of the paver blocks,  $H$  is the height of the parapet and  $w$  is the width of the building.

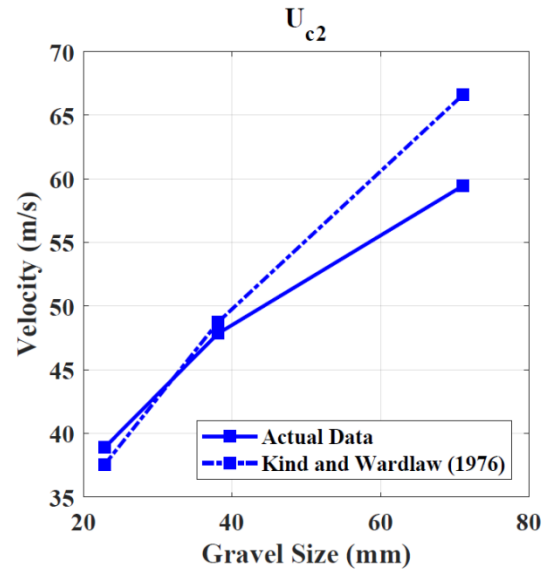


Fig. 8. Comparison of reference velocities from Table 2 with those recommended by Kind and Wardlaw (1976) for a high-rise building I.

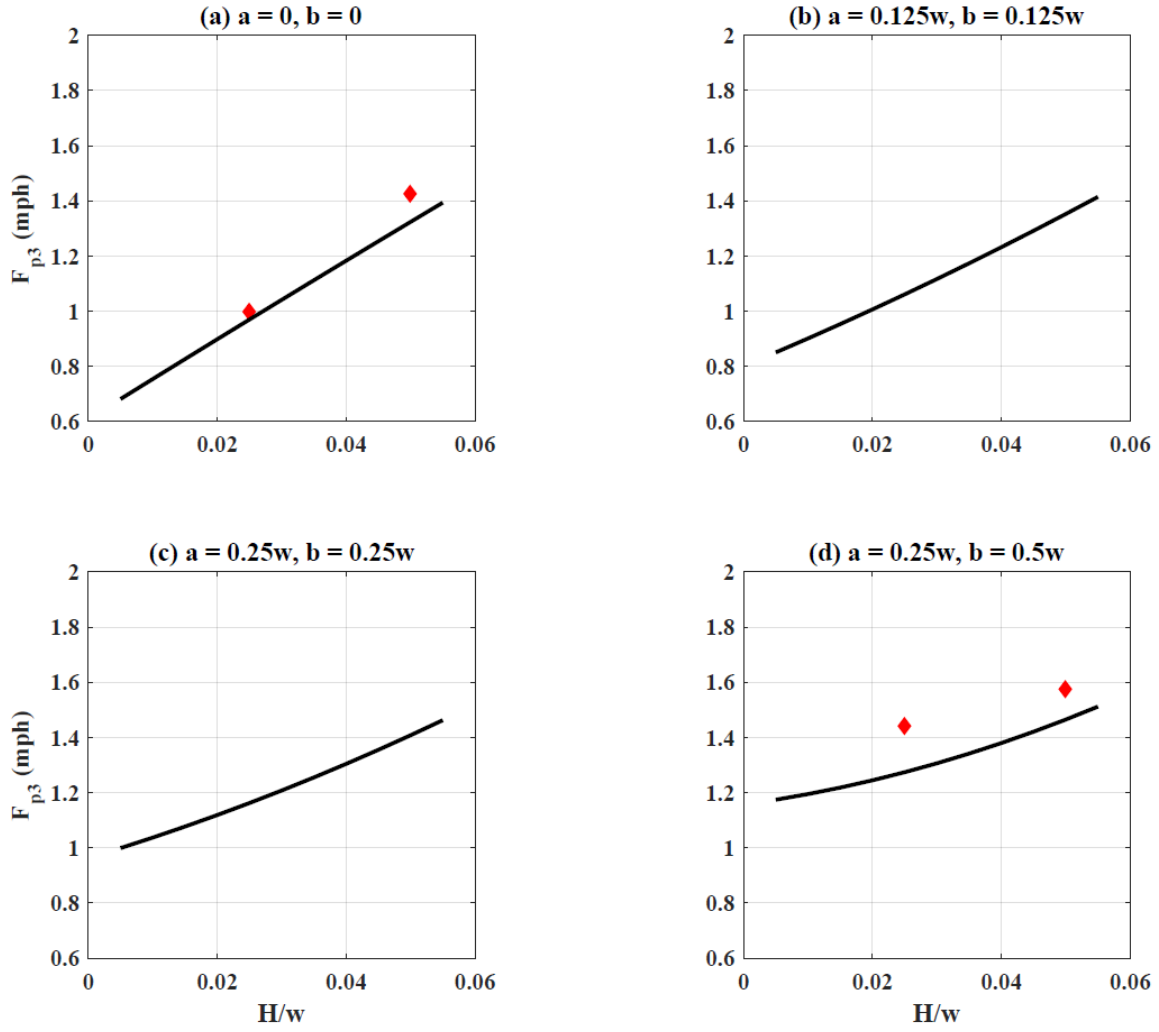


Fig. 9. Comparison of factor ( $F_{p1,2}$ ) for high-rise building II with experimental data from Kind (1975) (see Table 2) divided by critical scouring wind speeds ( $U_{c2}$ ) at  $H/w = 0.025$ ,  $a = 0$  and  $b = 0$  for gravel sizes corresponding to 22.9 mm, 38.1 mm, and 72.1 mm.  $a$  and  $b$  are the dimensions of the paver blocks,  $H$  is the height of the parapet and  $w$  is the width of the building.

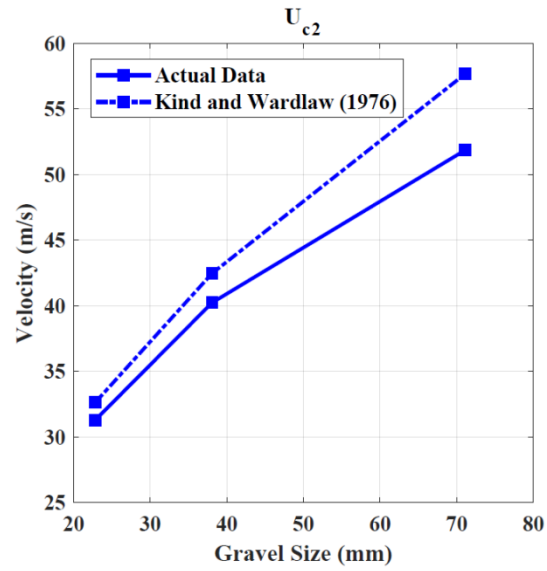


Fig. 10. Comparison of reference velocities from Table 2 with those recommended by Kind and Wardlaw (1976) for a high-rise building II.

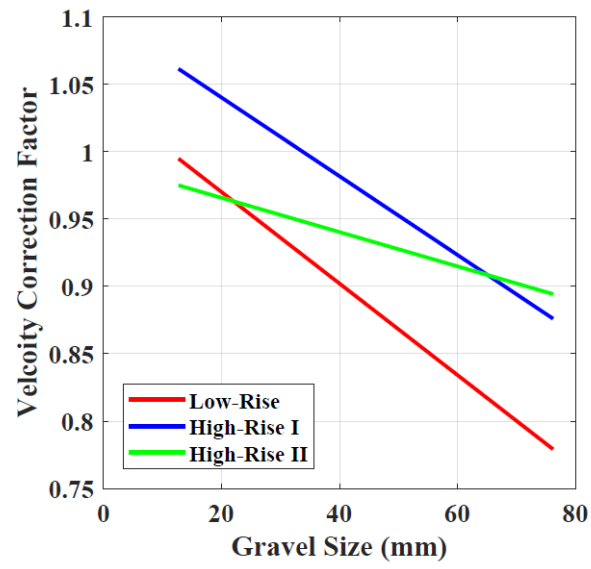
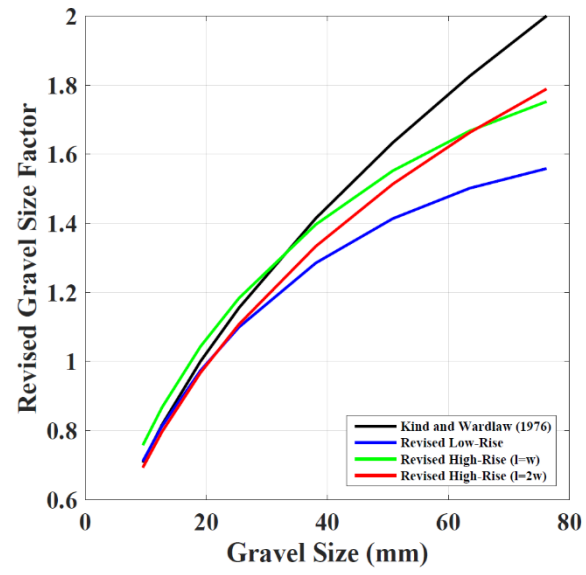


Fig. 11. Velocity correction factor low- and high-rise buildings based on Kind (1975) data.





646

647 Fig. 12. Revised gravel size factor.

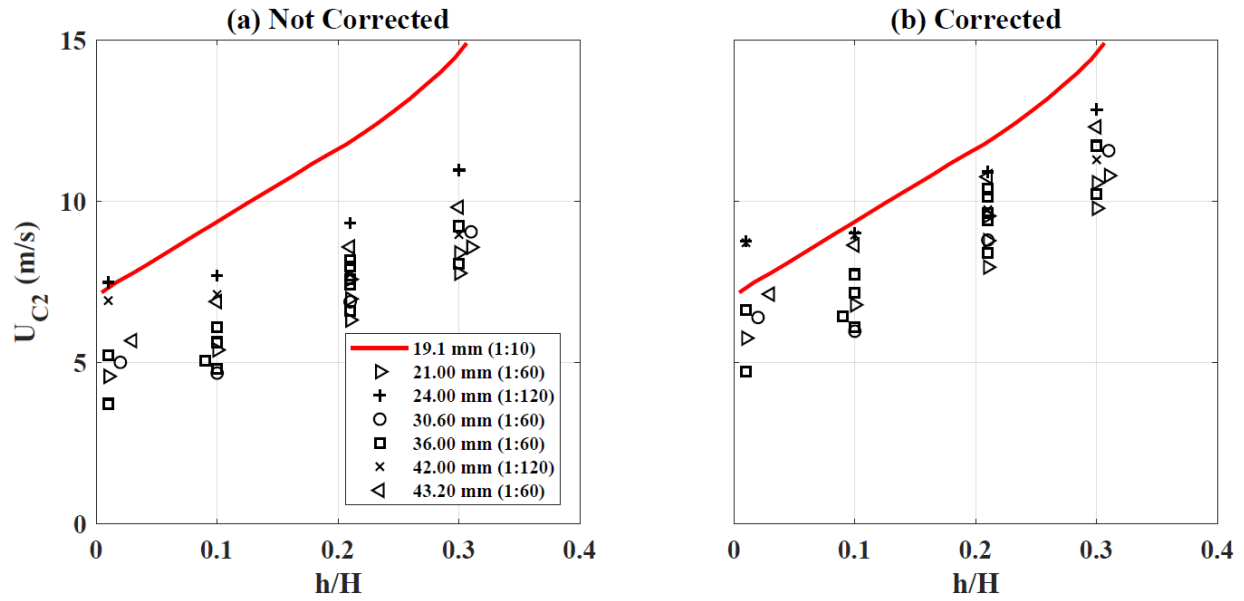


Fig. 13. Comparison of (a) uncorrected and (b) Reynolds number corrected (replotted from Karimpour and Kaye (2012)) model-scale critical scouring wind speeds at roof-height from 1:60 and 1:120 model scale experiments (Kind, 1986) with 1:10 model scale experiments (Kind, 1976) of a low-rise building. The solid line indicates the wind speed from Kind (1975) and the symbols indicate the wind speeds from Kind (1986).

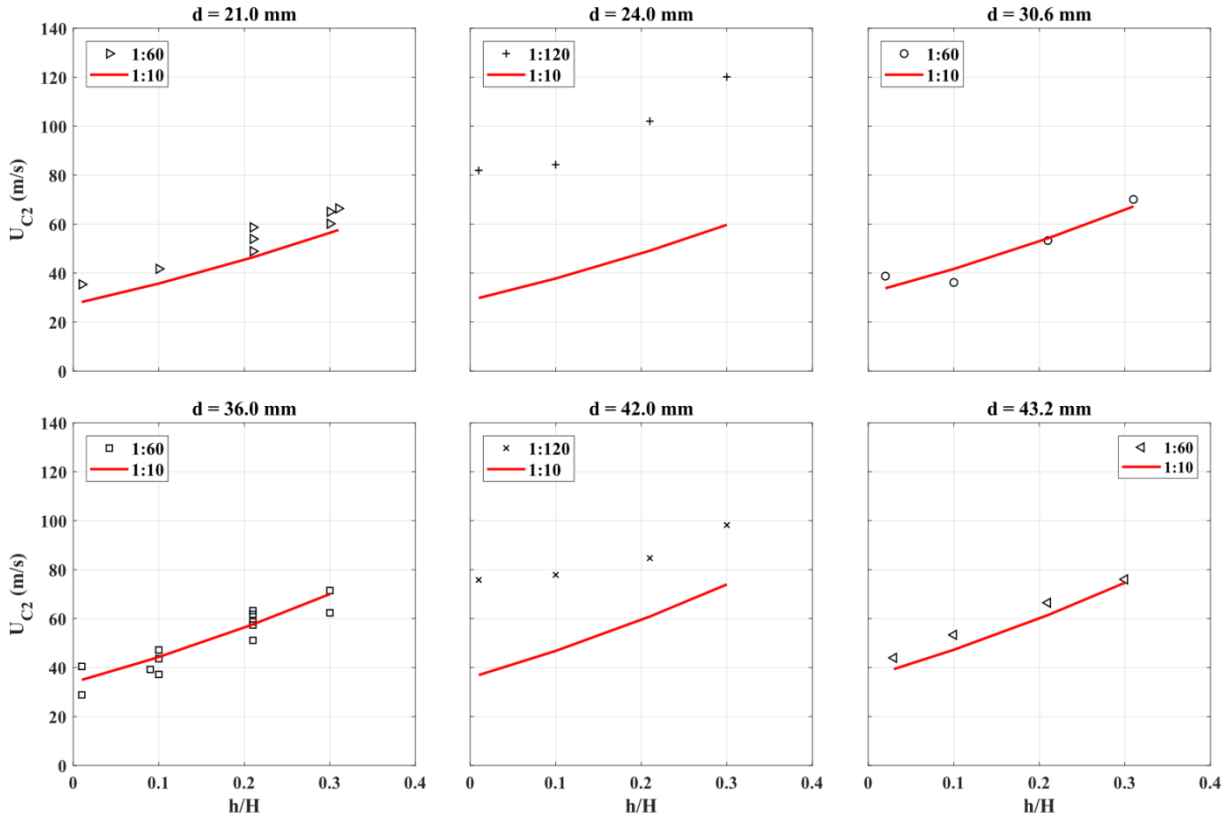


Fig. 14. The ratio of the full-scale critical scouring wind speeds at roof-height from Kind (1986) model scale experiments with Kind (1976) model scale experiments of a low-rise building (Kind, 1976).

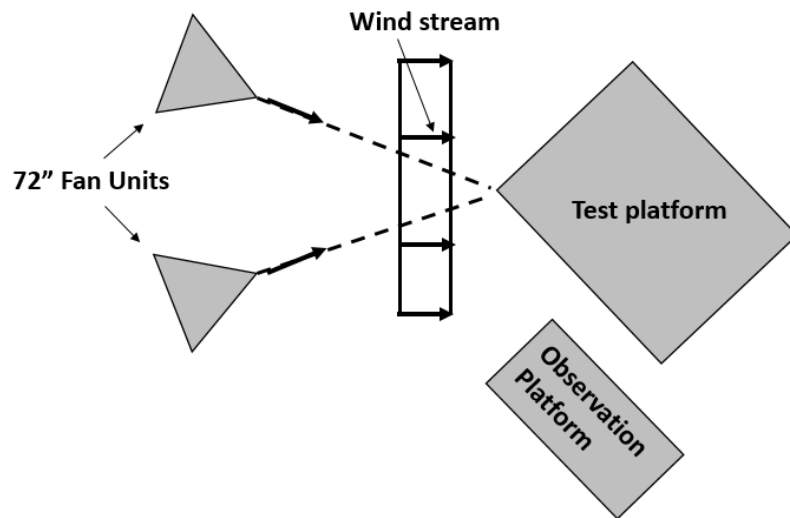


Fig. 15. Experimental setup used by Phalen (1984).

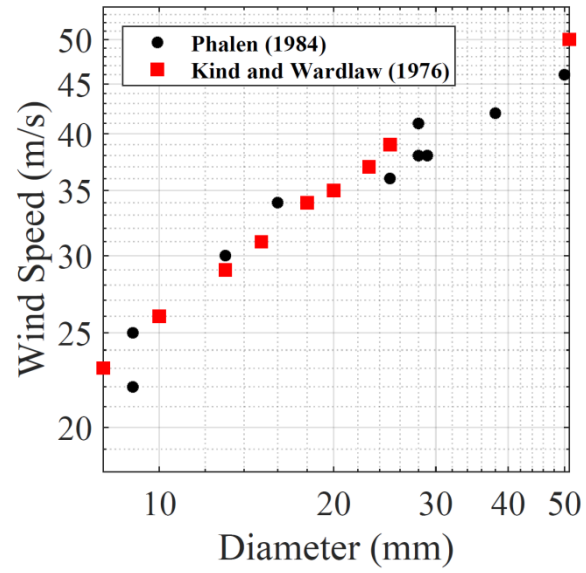


Fig. 16. Comparison of scouring wind speed as a function of stone diameter between Phalen (1984) and Kind and Wardlaw (1976) for the low-rise building with no parapet.

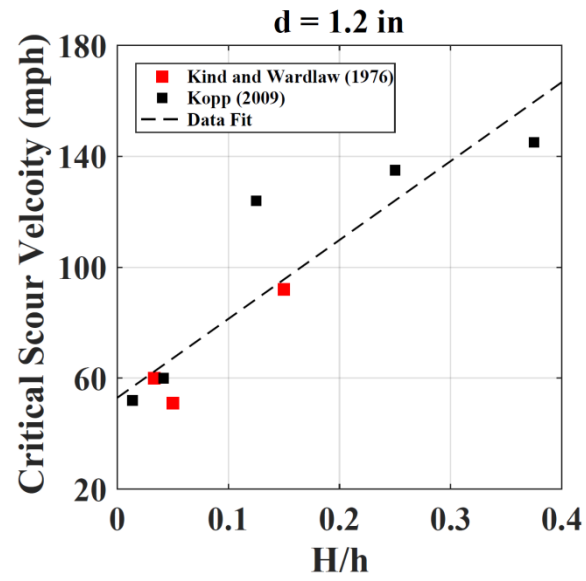


Fig. 17. Comparison of mean hourly critical scouring velocities for the low- to mid-rise building from Kind (1975) and University of Western Ontario that do not conform with Eq.(3).

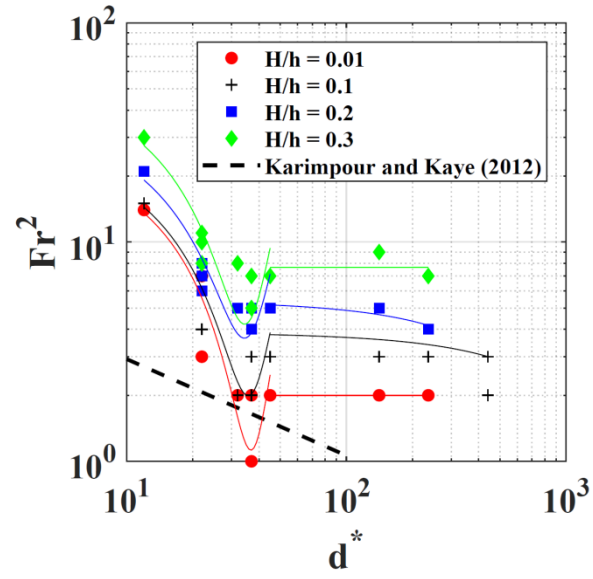
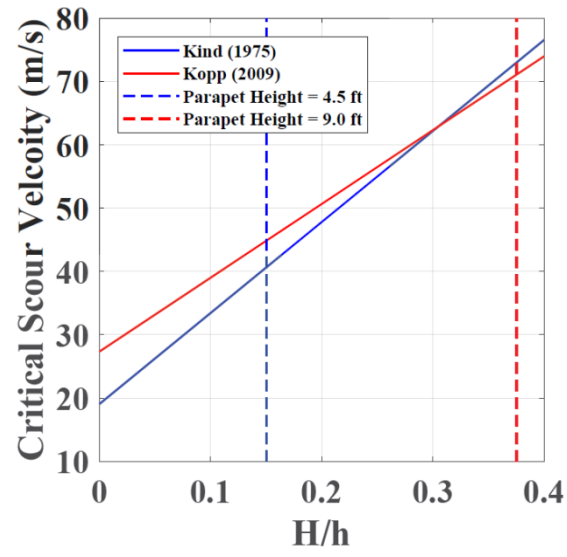


Fig. 18. Kind's (1975) critical scouring velocities for low-rise building plotted as  $Fr^2$  vs.  $d^*$ . The symbols represent the experimental data and the lines represents the data fit.



671

672 Fig. 19. Comparison of Kind's (1975) and Kopp (2009) data for low- to the mid-rise building.



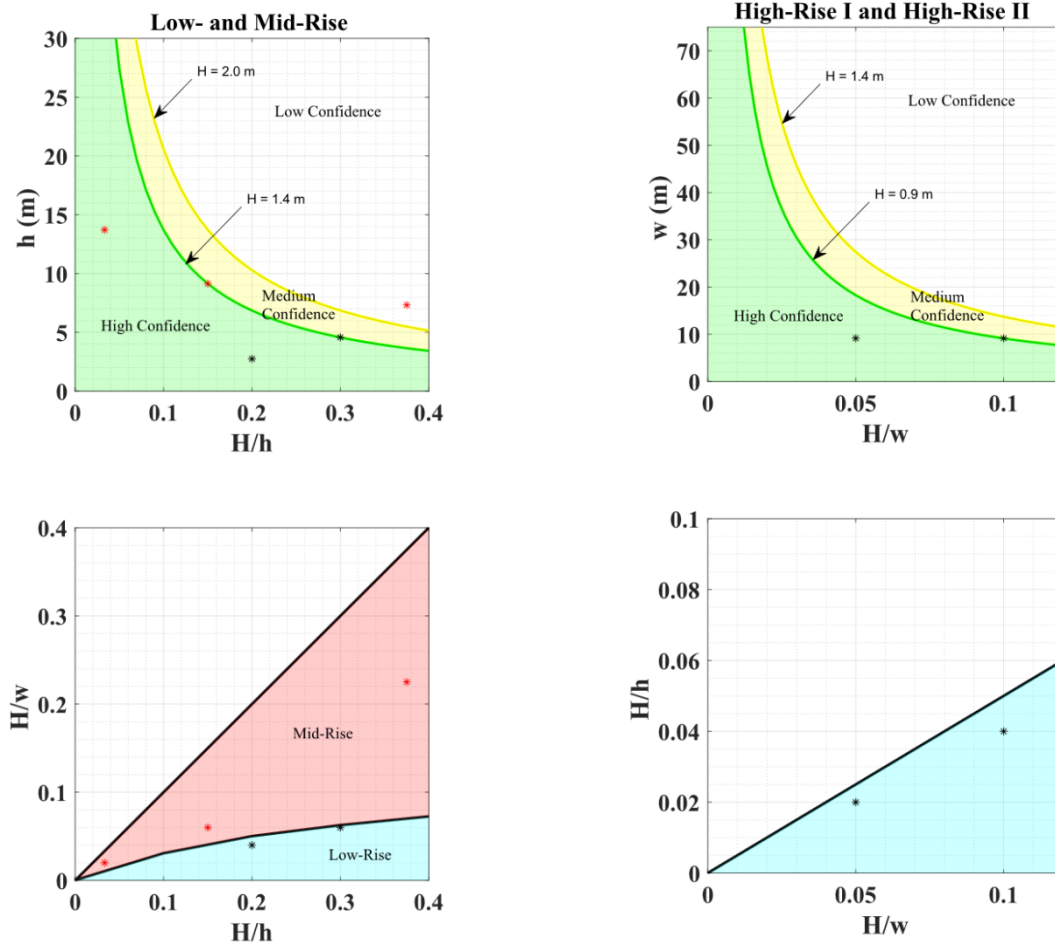


Fig. 20. (Top) Recommendations for confidence in parapet heights for low-, mid- and high-rise buildings. (Bottom) Envelope to qualify the buildings as low-, mid-, and high-rise. The symbols in the plots indicate the experimental data.  $H$  is the parapet height,  $h$  is the building height, and  $w$  is the building width.

677 Table 1. Gust factors used to convert mean hourly wind speeds at rooftop level to 1-s gust wind speeds for the data  
 678 presented in Table 2.

Building Height (m)	Gust Factor
2.74	1.62
4.57	1.6
9.14	1.55
13.72	1.5
22.86	1.2

679

680 Table 2. Equivalent full-scale data from Kind experiments (Kind, 1975).

Building Height (m)	Building Length (m)	Building Width (m)	Gravel Size (mm)	Parapet Height (m)	Paving Block Array Dimension (a x b) (m)	Wind Direction	$U_{C1}$ (m/s)		$U_{C2}$ (m/s)		$U_{C3}$ (m/s)		$U_{C4}$ (m/s)	
							1 s gust	Mean hourly	1 s gust	Mean hourly	1 s gust	Mean hourly	1 s gust	Mean hourly
4.6	68.6	22.9	38.1	0.06	None	45°	--	--	38.0	23.7	38.0	23.7	68.8	42.9
4.6	22.9	22.9	38.1	0.06	None	45°	27.5	17.0	40.2	25.0	38.0	23.7	55.0	34.4
4.6	22.9	22.9	22.9	0.06	1.14 x 1.14	45°	27.5	17.0	42.9	26.8	38.0	23.7	55.0	34.4
4.6	22.9	22.9	22.9	0.06	2.29 x 2.29	45°	40.2	25.0	47.8	30.0	47.8	30.0	51.9	32.6
4.6	22.9	22.9	22.9	0.06	2.29 x 4.57	45°	46.5	29.1	52.8	33.1	52.8	33.1	58.6	36.7
4.6	22.9	22.9	22.9	0.06	4.57 x 4.57	45°	46.5	29.1	56.3	35.3	55.4	34.9	58.6	36.7
4.6	22.9	22.9	22.9	0.06	4.57 x 9.14	45°	46.5	29.1	61.7	38.5	61.7	38.5	65.3	40.7
4.6	68.6	22.9	38.1	0.46	None	45°	39.3	24.6	50.1	31.3	51.4	32.2	68.4	42.9
4.6	22.9	22.9	22.9	0.46	None	45°	27.3	17.0	38.0	23.7	45.2	28.2	53.6	33.5
4.6	22.9	22.9	38.1	0.46	None	45°	41.6	25.9	51.9	32.6	51.9	32.6	62.6	39.3
4.6	22.9	22.9	38.1	0.46	None	45°	34.4	21.5	44.3	27.7	53.6	33.5	60.8	38.0
4.6	22.9	22.9	71.1	0.46	None	45°	45.2	28.2	55.0	34.4	64.4	40.2	70.2	43.8
4.6	22.9	22.9	38.1	0.46	2.29 x 2.29	45°	48.3	30.4	58.6	36.7	58.6	36.7	65.3	40.7
4.6	68.6	22.9	38.1	0.46	3.05 x 3.05	45°	51.4	32.2	58.6	36.7	68.4	42.9	72.0	45.2
4.6	22.9	22.9	38.1	0.46	2.29 x 4.57	45°	52.8	33.1	65.3	40.7	67.1	42.0	67.1	42.0
4.6	22.9	22.9	38.1	0.46	4.57 x 4.57	45°	52.8	33.1	65.3	40.7	65.3	40.7	65.3	40.7
4.6	22.9	22.9	38.1	0.46	4.57 x 9.14	45°	55.0	34.4	65.3	40.7	71.5	44.7	65.3	40.7
4.6	22.9	22.9	38.1	0.91	None	45°	48.3	30.4	58.6	36.7	64.4	40.2	64.4	40.2
4.6	22.9	22.9	22.9	0.91	2.29 x 2.29	45°	45.2	28.2	55.9	34.9	60.4	37.6	62.1	38.9
4.6	22.9	22.9	38.1	0.91	2.29 x 2.29	45°	58.6	36.7	62.1	38.9	68.0	42.5	72.0	45.2
4.6	22.9	22.9	38.1	0.91	4.57 x 4.57	45°	62.1	38.9	72.0	45.2	76.0	47.4	76.0	47.4
4.6	22.9	22.9	38.1	0.91	4.57 x 9.14	45°	65.3	40.7	79.6	49.6	82.7	51.9	82.7	51.9
4.6	22.9	22.9	22.9	1.37	None	45°	52.8	33.1	65.7	41.1	72.0	45.2	76.0	47.4
4.6	22.9	22.9	38.1	1.37	None	45°	48.3	30.4	72.0	45.2	82.3	51.4	82.3	51.4
4.6	22.9	22.9	38.1	1.37	2.29 x 2.29	45°	55.0	34.4	79.6	49.6	81.8	51.0	81.8	51.0
4.6	22.9	22.9	38.1	1.37	4.57 x 4.57	45°	67.1	42.0	79.6	49.6	82.7	51.9	82.7	51.9
4.6	22.9	22.9	71.1	0.46	None	30°/60°	51.4	32.2	65.3	40.7	72.0	45.2	>84.9	>53.2
4.6	22.9	22.9	38.1	0.46	2.29 x 4.57	30°/60°	48.3	30.4	62.6	39.3	62.6	39.3	69.3	43.4
4.6	22.9	22.9	38.1	0.46	None	90°	65.3	40.7	71.5	44.7	>84.9	>53.2	>84.9	>53.2
2.7	13.7	13.7	22.9	0.05	None	45°	25.9	16.1	32.6	20.1	32.6	20.1	42.5	26.4
2.7	13.7	13.7	22.9	0.05	2.74 x 2.74	45°	39.3	24.1	46.9	29.1	44.7	27.7	49.2	30.4
2.7	13.7	13.7	22.9	0.55	None	45°	40.7	25.0	49.6	30.9	55.4	34.4	59.0	36.2
2.7	13.7	13.7	22.9	0.55	2.74 x 2	45°	46.1	28.6	55.9	34.4	59.0	36.2	59.0	36.2
4.6	22.9	22.9	38.1	0.06	None	45°	72.4	45.2	>84.9	>53.2	>84.9	>53.2	>84.9	>53.2
9.1	22.9	22.9	38.1	0.46	None	45°	34.4	22.4	38.0	24.6	45.6	29.5	51.9	33.5
9.1	22.9	22.9	38.1	1.37	None	45°	49.6	32.2	68.8	44.3	77.8	50.1	77.8	50.1
13.7	22.9	22.9	38.1	0.46	None	45°	34.4	22.8	43.4	29.1	47.4	31.7	56.3	37.6
22.9	9.1	9.1	22.9	0.06	None	45°	24.6	20.6	30.4	25.5	28.2	23.7	34.9	29.1
22.9	9.1	9.1	22.9	0.06	1.14 x 1.14	45°	30.4	25.5	36.7	30.4	39.3	32.6	39.3	32.6
22.9	9.1	9.1	22.9	0.06	2.29 x 2.29	45°	34.9	29.1	39.3	32.6	39.3	32.6	39.3	32.6
22.9	9.1	9.1	22.9	0.06	2.29 x 4.57	45°	39.3	32.6	49.6	41.6	42.0	34.9	42.0	34.9
22.9	9.1	9.1	22.9	0.23	None	45°	30.4	25.5	38.0	31.7	39.3	32.6	39.3	32.6
22.9	9.1	9.1	22.9	0.23	1.14 x 1.14	45°	34.9	29.1	39.3	32.6	39.3	32.6	39.3	32.6
22.9	9.1	9.1	22.9	0.23	2.29 x 2.29	45°	39.3	32.6	43.4	36.2	43.4	36.2	43.4	36.2
22.9	9.1	9.1	22.9	0.46	None	45°	47.8	39.8	62.6	52.3	67.1	55.9	67.1	55.9
22.9	9.1	9.1	38.1	0.46	None	45°	60.8	50.5	74.2	61.7	74.2	61.7	74.2	61.7
22.9	9.1	9.1	71.1	0.46	None	45°	72.0	59.9	>83.2	69.3	--	--	--	--
22.9	9.1	9.1	22.9	0.46	2.29 x 2.29	45°	51.9	43.4	66.2	55.0	69.7	58.1	69.7	58.1
22.9	9.1	9.1	22.9	0.46	2.29 x 4.57	45°	56.3	46.9	66.2	55.0	74.2	61.7	65.3	54.5
22.9	18.3	9.1	22.9	0.23	None	45°	27.7	23.3	30.4	25.5	33.1	27.7	39.3	32.6
22.9	18.3	9.1	22.9	0.23	2.29 x 4.57	45°	33.1	27.7	43.8	36.7	43.8	36.7	43.8	36.7
22.9	18.3	9.1	22.9	0.46	None	45°	34.9	29.1	43.4	36.2	43.4	36.2	43.4	36.2
22.9	18.3	9.1	22.9	0.46	2.29 x 4.57	45°	39.3	32.6	47.8	39.8	47.8	39.8	47.8	39.8
22.9	18.3	9.1	22.9	0.91	None	45°	55.9	46.5	65.3	54.5	65.3	54.5	65.3	54.5
22.9	18.3	9.1	38.1	0.24	None	45°	60.8	50.5	>84.9	>70.6	>84.9	>70.6	>84.9	>70.6

682 Table 3. Summary of critical scouring velocities from Kind (1986) in model scale.

Model Scale	Parapet Height Ratio (H/h)	Gravel Size (mm)	Mean hourly $U_{C2}$ (m/s)
1:60	0.01	0.35	4.57
	0.1	0.35	5.39
	0.21	0.35	6.97
	0.21	0.35	6.32
	0.21	0.35	7.58
	0.3	0.35	8.40
	0.3	0.35	7.77
	0.31	0.35	8.57
	0.02	0.51	5.00
	0.1	0.51	4.67
	0.21	0.51	6.88
	0.31	0.51	9.05
	0.01	0.6	5.22
	0.01	0.6	3.72
	0.09	0.6	5.06
	0.1	0.6	4.80
	0.1	0.6	6.09
	0.1	0.6	5.63
	0.21	0.6	7.41
	0.21	0.6	6.60
	0.21	0.6	8.17
	0.21	0.6	7.58
	0.21	0.6	7.97
	0.3	0.6	9.23
	0.3	0.6	8.05
	0.03	0.72	5.68
	0.1	0.72	6.89
	0.21	0.72	8.58
	0.3	0.72	9.81
	0.01	0.35	4.57
1:120	0.01	0.2	7.48
	0.1	0.2	7.69
	0.21	0.2	9.32
	0.3	0.2	10.97
	0.01	0.35	6.92
	0.1	0.35	7.11
	0.21	0.35	7.73
	0.3	0.35	8.96

683

684 Table 4. Summary of critical scouring velocities from Phalen (1984) in full-scale.

Gravel Size (mm)	Mean hourly $U_{C2}$ (m/s)
9.0	22.06
9.4	24.66
12.7	30.13
16.5	33.94
25.1	36.00
28.4	37.69
28.6	38.22
28.2	40.72
38.0	41.55
50.3	45.84
63.5	50.17

685

686 Table 5. Summary of critical scouring velocities from Kopp (2009) in full-scale.

Building Orientation (deg)	Parapet Height (m)	Gravel Size (mm)	Surrounding Buildings	10 min wind speed at roof height (m/s)
0	0.10	30	No	60.8
	0.30	30	No	60.8
30	0.10	30	No	28.6
	0.30	30	No	28.6
	0.91	30	No	64.4
45	0.10	30	No	25.0
	0.10	30	Yes	32.2
	0.10	43	No	33.5
	0.30	30	No	28.6
	0.30	30	Yes	32.2
	0.30	43	No	35.3
	0.91	30	No	59.5
	1.83	30	No	64.4
	2.74	30	No	69.3

687

688 Table 6. Summary of calculations for non-dimensional particle diameter for different particle densities.

$d^*$	$\rho_p$ (kg/m <sup>3</sup> )	$T$ (°C)	$\rho_a$ (kg/m <sup>3</sup> )	$v_a$ (m <sup>2</sup> /s)	$g$ (m <sup>2</sup> /s)	$d$ (mm)
45	1500	-48.15	1.6	$0.935 \times 10^{-5}$	9.81	0.95
		51.85	1.09	$1.807 \times 10^{-5}$		1.30
	2000	-48.15	1.6	$0.935 \times 10^{-5}$		0.87
		51.85	1.09	$1.807 \times 10^{-5}$		1.18

689

690 Table 7. Equations for Kind and Wardlaw (1976) recommended and revised gravel size factors.

	Low-rise	High-rise ( $l = w$ )	High-rise ( $l = 2w$ )
Kind and Wardlaw (1976) recommendation	$F_S = \sqrt{\frac{d_p}{(19.1)}}$		
Revised recommendation	$F_S = 0.43 \ln(d_p) - 0.27$	$F_S = 0.49 \ln(d_p) - 0.39$	$F_S = 0.53 \ln(d_p) - 0.57$
Note that the particle diameter ( $d_p$ ) is in mm.			

691